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R & D PLANNING INVOLVING MULTICRITERIA DECISION ANALYTIC METHODS AT THE BRANCH LEVEL

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COLLABORATIVE PAPER SERIES ON COMPARATIVE ANALYSIS ON APPLICATION OF DECISION SUPPORT SYSTEMS IN R & D DECISIONS

This series of papers are a product of collaborative research coordinated through IIASA's Management and Technology Area. The collaborating institutions are Hungarian State Office of Technical Development (personnel: Anna Vari, Janos Vecsenyi, Laszlo David); Decision Analysis Unit, Brunel University, England (Personnel: Patrick Humphreys, Lawrence D. Phillips); All-Union Research Institute of Systems Studies, USSR (Personnel: Oleg. I Larichev).

The papers report case studies prepared by the personnel from the collaborating institutions based on their own, and their colleagues' work in their own institutions. They worked together as a team in developing the methods for the analysis of these case studies which are described in the first paper in the series.

IIASA provided support for this work through its telecenter for communication between the investigations, and provided facilities for short term meetings between the investigations at IIASA for development of case studies and their comparative analysis. Particular MMT staff were Ronald M. Lee, Nora Avedisians, and Miyoko Yamada, who is the editor of this series.

A summary of this comparative analysis, based on the first four case studies in this series was presented at the IFIP/IIASA Conference on *Processes and Tools for Decision Support*, Laxenburg, Austria, July, 1982.

The papers in this series are

1. Humphreys, P.C., A. Vari and J. Vecsenyi: Methods for analyzing the effects of application of Decision Support Systems in R & D decisions (CP-82-69).
2. Vari, A. and L. David: R & D planning involving multicriteria decision analytic methods at the branch level. (CP-82-73).
3. Vecsenyi, J.: Product mix development: strategy making at the enterprise level. (CP-82-74).
4. Larichev, O.I.: A method for evaluating R & D proposals in large research organizations. (CP-82-75).
5. Humphreys, P.C. and L.D. Phillips: Resolution of conflicting objectives in evaluating R & D projects involving collaboration between industry and higher education. (CP-82-xxx, forthcoming).

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R & D PLANNING INVOLVING MULTICRITERIA DECISION ANALYTIC METHODS AT THE BRANCH LEVEL

Anna Vari and Laszlo David

I. INTRODUCTION

An essential problem of research planning is to decide which R & D projects may contribute most effectively to the most important societal-economic goals within the limits of the available material and human resources. In Hungary this problem is usually manifested as a macro level budget allocation task carried out by state authorities (planning office, ministries, etc.).

Within this context, we examine the case of a Hungarian state authority responsible for a sector of services at the national level which has, from time to time, faced the problem of budget allocation among R & D projects. Because of the heterogeneity of the R & D activity in the field, the projects, as well as the phases of the usual decision-making processes, are arranged on a three-level hierarchy system comprising of main areas (first level), programs (second level), and tasks (third level).

In the organizational hierarchy, the Department of R & D Planning of this state authority is responsible for the first and second level planning, while the task (third) level planning is carried out by individual departments. Within divisions of the authority, there are two rounds* involved in the collation of suggestions relating to the expressed tasks, programs and areas:

1) The Department of R & D Planning evaluates the areas (first level) and programs (second level) for allocation of finance.

2) Given this information, the individual departments within each division make recommendations about the tasks relevant to their divisions, which are to be financed from the budget defined in round 1. These recommendations must be approved by a top level decision maker who is responsible for overall planning.

In as much as each second level program comprises a set of tasks which are not rigidly pre-defined, and similarly each first level area comprises programs which are not rigidly pre-determined, the decisions arrived at sequentially are not necessarily consistent. In the interest of resolving possible conflicts, project evaluation is usually carried out in an iterative manner, and re-examined from time to time. The need for more clearly established and better organized rounds as well as the need for harmony across the different rounds motivated the decision makers of the authority involved in R & D planning to initiate the development of a suitable procedure formalized as a Decision Support System (DSS).**

* The definition of "rounds" to be used in this paper is given in Humphreys et al. (1982).
** The definition of "Decision Support Systems" to be used in this paper is given in Humphreys et al. (1982).

In our investigations we summarized our experiences with the DSS in decision analyses related to two different rounds. In the first case, decision analysis was initiated by one of the divisions which had to make a budget allocation decision between seven third level tasks (Analysis A). The method for the decision analysis as well as the supporting computer software were developed by a team of outside consultants. The second problem to be resolved was the consistent allocation of the budget on the first and second levels which means allocation across five areas and 20 programs. The analysis of the problem, by using the method and procedures developed in Analysis A with minor modifications, was initiated by the decision makers of the Department of R & D Planning (Analysis B).

II. RESPONSIBILITY AND MOTIVATION OF DECISION MAKERS AND PROPOSERS

It is important in a multilevel system like this to distinguish between the responsibility and motivation of *decision makers* and *proposers*.

Decision makers of the Department of R & D Planning were responsible for the budget allocation among all candidate R & D projects. The projects comprised all of the main areas of R & D activity and, of course, higher level decision makers cannot be competent in each of these areas. In using a DSS, decision makers were motivated by the opportunities it provided for (i) rationalizing their decisions by basing them on more reliable information, (ii) having a tool for explaining (justifying) their decisions to their subordinates (to the managers of the competing areas, programs, etc.) and (iii) modernizing their decision making practice.

Proposers (in this case, leaders of the divisions) were responsible for making suggestions to higher level decision makers as to which R & D tasks of their particular area should be supported. They were more competent in their area than higher level decision makers, although they needed the help of *experts* who were familiar with the details of the R & D tasks. In using DSS, *proposers* were motivated by the possibility of (i) influencing the decision makers by using more efficient tools, (ii) eliciting information from experts, and (iii) learning new methods for modernizing their own decision making practice.

Because of the different responsibilities and motivation of the decision makers, we would expect the function of the results for these two classes of users expected from the (same) DSS used in Analyses A and B to be quite different. We found that *decision makers* expected to use the results for (i) prescription for action (e.g., rank order of R & D programs in terms of cost-effectiveness) which would, at least partly, relieve them of the responsibility for such actions, and (ii) as rationalization for actions they might wish to take.

On the other hand, *proposers* expected to use the results for (i) gaining a better insight into the decision problem (e.g., simulation of the consequences of the possible choices, multiple criteria analysis of the options, etc.), and (ii) communication of information.

III. THE DECISION SUPPORT SYSTEM

A. Methodological Requirements

The basis of decisions on the financing of R & D projects is the evaluation of each project and the comparison of these evaluations. The comparison is obviously more problematic in the case of branch level decision than on company or institute levels. At a lower level, since the R & D projects are relatively homogeneous, not too different in content, it suffices to evaluate them according to some more or less well determined criteria. In case of higher level decisions, a whole system of qualitatively different but highly interdependent criteria have to be considered. A further difficulty is imposed by the fact that R & D decision problems usually involve a great amount of uncertainty as far as the success and effectiveness of research, the use of research results, as well as the success of implementation are concerned.

In the selection of projects, it should also be taken into consideration whether R & D activities in the different phases of the innovation process are being compared which, because of the interrelationships, require parallel or sequential accomplishment.

In view of the above, certain requirements for the DSS to be used in R & D planning decision can be outlined.

1. They should help — at the given decision level — in exploring the social-economic criteria deemed most important, in forming a unified interpretation and in evaluating the R & D projects according to these criteria.

2. They should enable the decision makers and proposers to express their uncertainties concerning the successful completion of the projects as well as the successful implementation of the results.

3. They should enable the adequate consideration of the relationships among the projects.

4. As far as possible the simplification of judgments in complex decision situations and the biases stemming from the lack of information should be eliminated. For this purpose the involvement of experts as well as their interaction should be facilitated.

5. Since decision should, from time to time, be repeated in view of the changing goals, conditions as well as new R & D projects, an essential requirement is the relative simplicity and easy reproducibility of the analysis.

The consultants' goal in this case was to develop a DSS which would satisfy all five of the criteria.

B. Stages in the Round

The *consultants* proposed that each round should be conceptualized as a budget allocation problem, and therefore the stages in the round would be those required to compute, as a basis for decision, the subjective expected utility (SEU) for each R & D project or, in the case of project interdependencies, project combination. SEU was accepted as a basis for "decision making" by the *proposers* who were responsible for initiating the use of the DSS. The *consultants* (decision analysts) proposed direct optimization algorithms for budget allocation on the basis of the SEU of projects, but this was refused by the *proposers* (reasons why the proposers acted in this way will be discussed below). In view of this, the following stages were agreed to constitute the round.

1. Definition of the set of projects to be evaluated.
2. Exploration of the evaluation criteria.
3. Determination of weights of criteria.
4. Definition of utility functions on individual criteria.
5. Estimation of the uncertainties related to the successful research and implementation of the projects.
6. Evaluation of the projects (project combinations), through computing their SEU in terms of the criteria.
7. Multiciriteria aggregation of data.
8. Selection of projects to be supported.

C. Definition of the Sets of Projects To Be Evaluated

Assuming that individual projects are only made possible by the allocation of specific funds for their implementation, the set of decision alternatives comprises all feasible combinations of the R & D projects which can be financed from the given funds. The SEUs of the project combinations can only be obtained through summing the SEUs of the individual projects, if there are no interdependencies amongst the projects. If there is a complementary relationship among the projects then the SEU of the joint execution of the projects is greater than the sum of the

SEUs of the projects executed individually. If, however, the projects are competitive, the SEU of the joint execution is less than the total of SEUs of the projects executed individually. Consequently, in cases where interdependencies exist between projects, the SEUs have to be defined outside the individual projects for all feasible combinations of interdependent projects as well.

However, it must be noted here that revealing the interdependencies between projects can cause conflicts of interest. It emerged, for instance, that only when united as a single program can they be executed appropriately. If this involves uniting programs in different areas, this can generate a conflict of area leaders' interest. (We shall see examples of this during Analysis B).

The revelation of hidden overlappings (inter-project competitive connections) can also cause conflicts. Hence, in the interest of eliminating biases arising from the conflicting interests of the proposers and decision makers it was considered reasonable to include in this phase as many outside experts as possible.

D. Exploration of the Evaluation Criteria

Because of the complexity of the problems, it was necessary to introduce a method that would make it possible to embrace a wide set of criteria. Whereas decision makers are not able to work with an unlimited number of criteria, this does ensure that the criteria finally adopted for use will be of adequate scope. At this point decision analysts are faced with two possibilities. One, which we could call the "a priori" method, involves calling up an expert or a group of experts to develop the final set of criteria directly. The other, which we could call the "empirical" method, starts with a set of criteria volunteered under various views, free of any pre-considerations of their relative importance, and then employs empirically-based techniques to reduce this set to the final set of criteria to be adopted for use.

The advantage of the a priori method is that it immediately generates a clearly defined set of criteria. However, the basis for the selection of criteria suffers from the variety of confusions identified in research on human information processing (Kahneman and Tversky 1973). These include effects of previous preferences, and illusions of validity stemming from the simplification of opinion formation processes.

If one opts instead for the utilization of the empirical method, one has to deal with significant difficulties introduced through the use of the criterion processing methodology. However, the advantage of this approach is that it excludes the above mentioned confusing factors. Taking all this into account, it appeared desirable on objective grounds to choose the latter method.

The essence of the empirical method employed in this case is that the criteria initially collected through brainstorming, are subsequently filtered by the participants, who then classify them. The results of the classification are then processed and cluster analyzed by the computer. The clusters gained in this way can be formed into higher level criterion categories, which, more or less, satisfy value-independence condition.

It is very important that proposers and decision makers take part in the definition of the evaluation criteria, although participation of the latter, as we shall see in the case of Analysis B, often encounters obstacles.

E. Determination of Weights of Criteria, and Definition of Utility Functions on Individual Criteria

The first step in this process consisted of defining the end points of the criterion scales. Following this, the weights of the criteria were determined by making paired comparisons between part-worths of criteria (ranging between the "worst" and "best" anchor on each criterion). The frequency of preference for each criterion, summed over subjects and comparisons, was transformed to give the criterion weight, using the Guilford transformation (Thorndike 1920).

The next step was to scale the utility function on the elicited "part-worth" values of each criterion. The method of estimating this function was based on finding utility quartiles (Raiffa 1968). It would have been desirable for the proposers and decision makers to be present for the definition of the criterion weights and utility functions but, for reasons similar to those discussed above for the first stage, this was problematical, and so these activities were in fact carried out by the experts.

F. Estimation of Uncertainties and Evaluation of Projects

1. Analysis A

Because of the lack of historical data in the comparison of R & D projects, subjective elements (probabilities, utilities) play an especially important role. It was for this reason that the consultants suggested that the evaluation of the R & D projects should be made on the basis of their subjective expected utility (SEU).

There were three types of uncertainty considered while estimating the SEU of each project: the uncertainty related to the successful accomplishment of the research, that related to the implementation of the research results and that related to the benefits of application. On the other hand, in computing the SEU it was necessary to estimate first the maximum utility to be achieved in case of full success of research and implementation (maximum feasible utility of a project). The project's SEU was then obtained by weighting maximum feasible utility by the subjective probabilities expressing uncertainties about whether it could be achieved. In course of Analysis A, the consultants suggested the following subjective probabilities be assessed for each research project(j):

P_{1j} : the probability of the successful accomplishment of the j-th research

P_{2j} : the probability of implementing the results of the j-th research (given that it had been successfully accomplished)

P_{3j} : the probability of the successful application of the results (given that they had been implemented)

The subjective probabilities P_{1j}, P_{2j}, P_{3j} were estimated through the use of a gambling method (the "minimal selling price" method, see MacCrimmon (1973)). Following this, the maximum feasible value of the projects in terms of elicited ratings on each criterion ($\hat{x}_{ij}$) was estimated.

The utility functions estimated previously for each criterion were used to transform these values into maximum feasible utilities of each projects: on each criterion, (i), defined as $u_i(\hat{x}_{ij})$. The subjective expected utilities of the projects (SEU_{ij}) could now be calculated in the following manner:

Either

$$SEU_{ij} = P_{1j} \cdot u_i(\hat{x}_{ij}) \tag{1}$$

if the i-th criterion was connected with the benefits deriving from the direct results of the j-th research;

or

$$SEU_{ij} = P_{1j} \cdot P_{2j} \cdot P_{3j} \cdot u_j(\hat{x}_{ij}) \tag{2}$$

if the i-th criterion was connected with the benefits deriving from the application of the R & D results.

2. *Analysis B*

The above method had to be refined in course of Analysis B. Here, the procedure was not to assess the individual (maximum feasible) values of the project's overall criteria, but rather to assess the probabilities of the realization of the different values of the individual criteria. These assessments were expressed as probability density functions by criteria. Multiplying these with the utility functions the subjective expected utilities in terms of criteria can be obtained:

$$SEU_{ij} = \int_{x_i min}^{x_i max} P_{ij}(x_i) \cdot u_i(x_i) dx_i \tag{3}$$

where

SEU_{ij} : is the expected value of the utility of the j-th project in terms of the i-th criterion

$u_i(x_i)$: the utility function along the i-th criterion

$P_{ij}(x_i)$: the probability density function of the j-th project in terms of the i-th criterion

x_i min, x_i max : the end points of the i-th criterion scale.

In practice the P_{ij} probabilities were estimated for five intervals and were regarded as constant within the individual intervals. In this way the integral in equation (3) was simplified to a weighted summing.

The estimation of uncertainties and the evaluation of projects in terms of criteria was carried out by groups of experts in both analyses. In course of Analysis A, the divergent news were reconciled through discussion, while in course of Analysis B due to the great number of experts statistical aggregation was used for overcoming them.

G. Multicriteria Aggregation of Data, Selection of the Projects to Be Supported

Knowing the subjective expected utilities in terms of criteria (SEU_{ij}) and the weights of the criteria (W_i) the overall subjective expected utility of the j-th project (SEU_j) can be determined as follows:

$$SEU_j = \sum_i W_i \cdot SEU_{ij}$$

This gives a possibility for rank-ordering the projects as well as feasible project combinations. However, as we will see in Analysis A, the final selection of the projects to be supported may be based not only on SEU but on some additional criteria not considered explicitly in course of the analysis.

IV. EXPERIENCES OF ANALYSIS A

In Analysis A, the problem was of budget allocation between seven R & D tasks (third level projects). The decision analysis was initiated by the proposers, that is, the leaders of the affected division. The procedure for Analysis A described in the previous section was applied in the evaluation of seven individual projects and three combinations of these projects. The analysis comprised 14 higher level criteria, which were derived from 164 elementary criteria. The determination of criterion weights, utility functions, the assessment of probabilities and the criteria-wise evaluations were carried out, altogether, by 15 participants (proposers and experts). The decision makers were not involved in these stages of the analysis.

The proposers mediated between decision makers and all other parties. This meant that they had to (i) anticipate the criteria, expectations, preferences, etc. of the decision makers, and (ii) determine the way that the outputs from Analysis A served as inputs to higher level decision making.

The proposers wanted to participate in the determining of criteria, weights, probabilities and utilities *as experts*. On the other hand, they wanted to influence the decision makers and for this purpose they wanted to have the freedom of manipulating the results. Therefore, they preferred having an insight into the consequences of the possible actions (choices) instead of receiving a direct prescription resulting from the use of optimization algorithms. For the same reason they preferred to consider only a certain part of the whole problem structure (i.e., some but not all relevant criteria) simultaneously in the course of the formal decision analysis process and to take the other components into consideration intuitively while making proposals. This preference can be used to explain why, although at the beginning of the analysis SEU had been accepted as a basis for "decision making," at the end of the round in forming the final proposal the proposers more or less neglected SEU. Instead, they now took other aspects (importance, cost, time factor) — which had not been represented as criteria in computing.

While the *proposers controlled the information flow between decision makers and the other participants* of the analysis, the *gathering and processing of information and the use of computerized decision aids was controlled by the decision analysts.* A computer was used in stage 2 for clustering the criteria, in stage 3 for determining the weights of criteria by Guilford transformation of preference frequencies, in stages 4-6 for computing group statistics and in stage 7 for multicriteria aggregation of the estimates resulting from the earlier stages.

The scheme of the information flow and the interfaces between the parties is summarized in Figure 1.

It is evident from the figure that the decision analysts, the experts and the computer algorithms do not actually help the decision makers but do help the proposers. Those findings relate to those of von

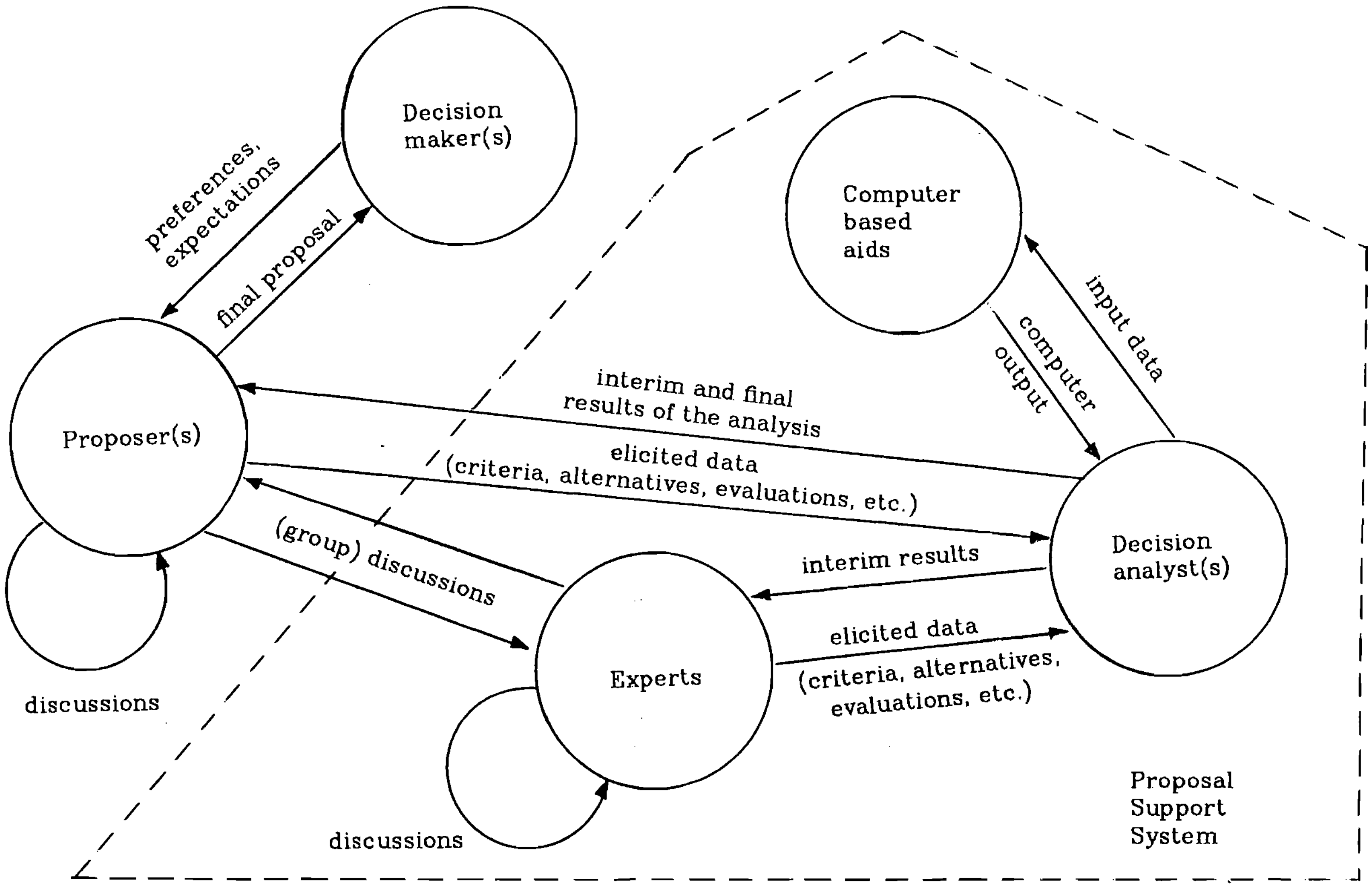

Figure 1. **Channels of communication during Analysis A.**

Winterfeldt (1980), who discusses how Multiattribute Utility Theory (MAUT) based systems such as the DSS used here are inappropriate for *decision* analysis in resource allocation problems. However, given the motivation of the proposers, discussed in section II, it appears that the DSS in this case met the goals of the proposers through being perceived as a *proposal* support system (hence the emphasis on its simulation capability) rather than as a *decision* support system. Understanding the role of the system here as a PSS sidesteps von Winterfeldt's criticism of the use of MAUT (since the problem context is changed) and this may have provided the key to its success.

The claim that the system was successful in this way is supported by the fact that shortly after Analysis A was completed the team of the designers (decision analysts) obtained a commission from the same authority to expand the procedures of Analysis A into a form suitable for the evaluation of *higher* level R & D projects. These were located at the first and second level, and the next section describes the analysis that was developed from Analysis A in performing this evaluation task.

V. EXPERIENCES OF ANALYSIS B

Analysis B was initiated by the leader of the Department of R & D planning in order to obtain support in budget allocation among five areas and 20 programs contained therein. This comprised the whole middle-range R & D planning scope of the authority for the subsequent five years plan period, which in turn justified the need to bring a relatively large number of experts (about 40) into the analysis.

The first stage consisted of carrying out an investigation of project interdependencies. In the course of the analysis it emerged that the hierarchy within which projects were currently represented was not reasonable. The linkage within this hierarchy was based on an organizational structure rather than on professional considerations. Specifically, it became evident that the programs assigned to, and thus clustered together within area No. 5 of the hierarchy had very loose connections with each other, while being more closely related to some programs in other areas. For this reason, the experts made recommendations for grouping the set of the programs within four areas.

The restructuring of the project hierarchy was followed by the exploration of the evaluation criteria. This time 12 criteria were defined which had little overlap with the criteria explored in course of Analysis A. This lack of overlap is not surprising because the criteria considered as a basis for the higher level decisions were primarily connected with general socio-economic goals, while in the evaluation of tasks (Analysis A), criteria which prevailed were those reflecting the special interests of divisions.

The next stage consisted of carrying out the multicriteria evaluation of the programs (second level) and areas (first level). In order to verify the consistency of the evaluations, the rank preference order obtained for the areas was compared with the rank order obtained by making an aggregate evaluation of the programs enclosed within each of the individual areas. Because of the union of closely dependent programs which was in stage 1, it seemed reasonable to regard each area as comprising a set of independent programs, and so the SEU of each area was obtained through the summation of the SEU of the programs within it.

The comparison revealed that while the best and worst areas were the same according to both rank orders, the rank orders of intermediate areas between the two extremes did not agree. In deciding between these ambiguous orderings, the decision makers considered that the ***rank order based on the aggregate evaluation of the programs*** should accepted as valid in the course of budget allocation on both the first and the second level.

It is also necessary to consider whether it is possible to eliminate the suboptimality of decisions originating from the sequential character of the budget allocation among tasks and programs.

In theory, Analysis B required the simultaneous comparison of all the 66 tasks at the third level in determining which tasks and second level programs would receive support. However, in setting up the analysis required for such a solution the consultants had to face serious methodological problems related to the comparability of the evaluations given by different experts for the different subsets of tasks: none of the experts could evaluate ***all*** the 66 tasks. On the other hand, as we have seen, the evaluation criteria on the different levels of decision making as well as in the different divisions are qualitatively quite different. The attempt to formulate a "common denominator" of the special divisional criteria encountered significant difficulties. Thus the aggregation of the lower level analysis for supporting the higher level decision making proved to be unsatisfactory. Hence it was reasonable to maintain independence of the different rounds at the three levels of the decision making.

As described earlier, relatively large number of experts took part in the representation of various fields in the phases of Analysis B. In view of this, the consultants found it quite surprising that the members of the Department of R & D Planning could not also be involved in this analysis, despite the fact that the work was initiated by them. Originally, the plan was to involve them in the analysis, particularly in determining and weighting the criteria, but they refused to participate. They required only a one-way channel which served to communicate the essence of the experts' views (see Figure 2).

The negative consequences deriving from the lack of participation of the decision makers were related to the opposition to the consultants' proposals by some members of the Department of R & D Planning (managers of R & D programs). Some did not agree with the regrouping of the R & D programs and the splitting up of the fifth area. They demanded proposals fitting within the original 5-area hierarchical structure of the programs. These managers' opposition to other proposals was connected with their interest in the maintenance of the five areas.

Others cited the incomparability of criteria and argued in favor of the superiority of the intuitive decisions. These opinions probably arise also from conflicting interests being served by opposing the results of the analysis. At the same time the results of the analysis found a positive reception with the head of the Department of R & D Planning. For him, the analysis gave a satisfactory justification for his decision amongst the parties and their conflicting interests in the evaluation of programs.

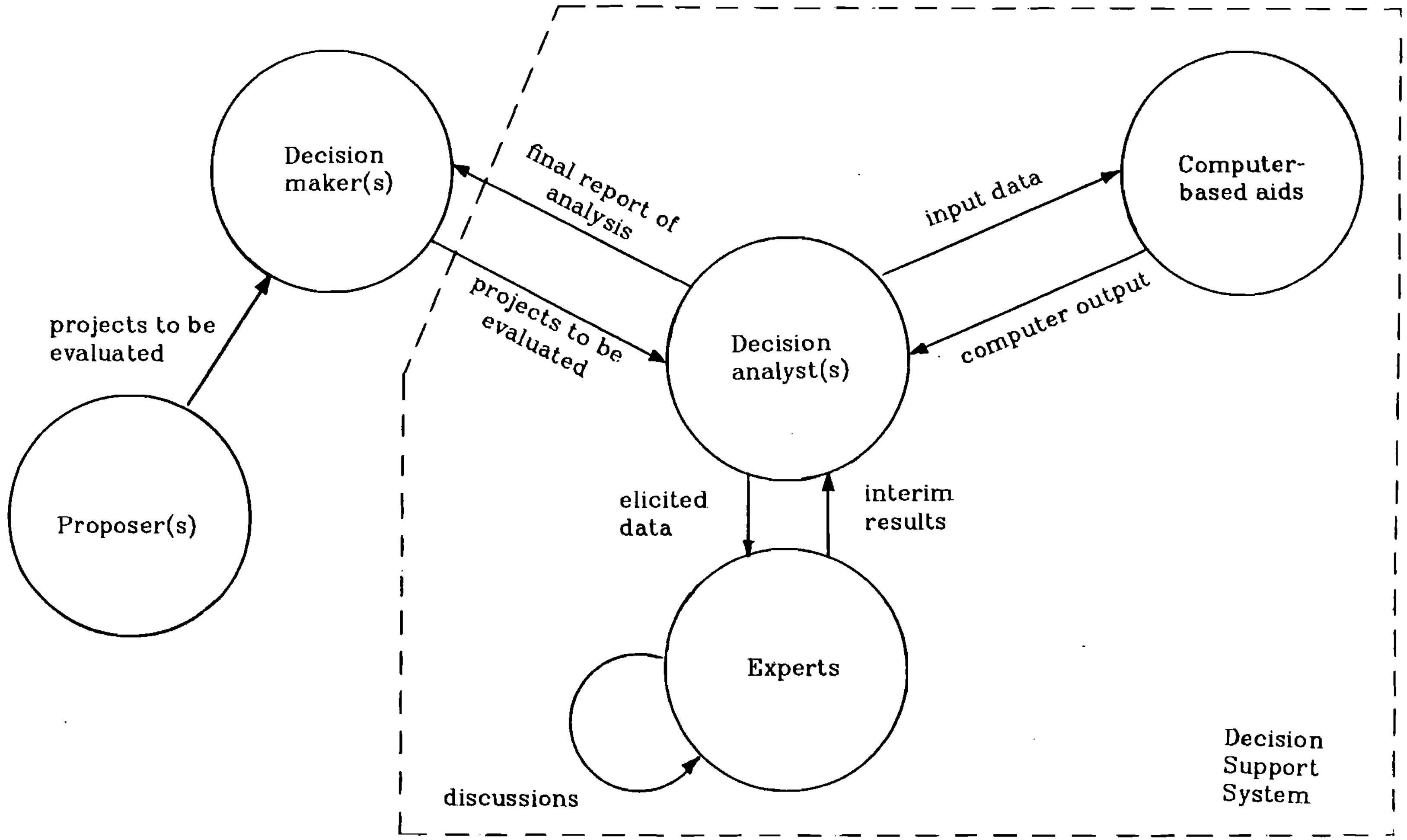

Figure 2. Channels of communication during Analysis B.

VI. CONCLUSION

These methods for R & D budget allocation described in Analyses A and B proved to be satisfactory for supporting the individual rounds in deciding a budget allocation. However it cannot eliminate that sub-optimality which is connected with the sequential character of decision making which, in this case, is the consequence of the hierarchical division of roles and responsibilities.

It was also found that, if between the system and the decision makers there are no mediators who know of the latter's preferences, preconceptions and acceptance limits, confusions may arise during the process of acceptance of the results gained through the application of the decision support system.

It became obvious during our investigations that a *proposal support system* developed for use by proposers, cannot also be utilized in the same form as a decision support system for higher level decision makers considering those proposals. There are two reasons for this: (i) the motivation of the proposers and the decision makers is different, (ii) even when decision support systems developed for use at different levels have the same overall structure (multi-attribute utility theory in our case, c.f. Humphreys (1977)) the structure at each level must have *qualitatively* different characteristics. In our case, the criteria appropriate for use in second level decision making were qualitatively different from those used in third level decision making. We consider these findings on the nature of what constitutes as "requisite" DSS (Phillips 1982) to be one of the most important results of this case study.

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